Scintillator Tile Hadron Calorimeter with Novel SiPM Readout

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Abstract

The CALICE collaboration is presently constructing a test hadron calorimeter (HCAL) with 7620 scintillator tiles read out by novel photo-detectors - Silicon Photomultipliers (SiPMs). This prototype is the first device which uses SiPMs on a large scale. We present the design of the HCAL and report on measured properties of more than 10 thousand SiPMs. We discuss the SiPM efficiency, gain, cross-talk, and noise rate dependence on bias voltage and temperature, including the spread in these parameters. We analyze the reasons for SiPM rejection and present the results of the long term stability studies. The first measurements of the SiPM radiation hardness are presented. We compare properties of SiPM with the properties of similar devices, MRS APD and MPPC. A possibility to make the tiles thinner and to read them out without WLS fibers has been studied.

1. Introduction

The physics requirements at the International Linear Collider (ILC) impose high demands on the performance of calorimeters. The ultimate goal is to achieve a jet energy resolution of about $30\%/\sqrt{E}$, in order to increase the sensitivity for reconstruction of the W, Z and Higgs bosons and supersymmetric particles. Monte Carlo studies have indicated that this goal can be achieved by utilizing the Particle Flow (PF) method. In this approach energies of neutral particles (photons, neutrons, and K_L) are measured in calorimeters while charged tracks are measured with a better precision in the tracker. The showers produced by charged particles should be removed from the calorimetric measurements. This method requires a very high calorimeter granularity in order to reconstruct showers produced by neutral particles in a vicinity of showers produced by charged particles. The PF method defines to a large extent the whole architecture of the ILC detector. So far the PF method is studied mainly with MC. These studies demonstrated that a very high granularity of about 3×3 cm^2 is required. Such a granularity can be achieved with the novel photo-detectors developed in Russia, Silicon Photomultipliers (SiPMs) [1]. The CALICE collaboration is presently constructing a test hadron calorimeter (HCAL) with 7620 scintillator tiles read out by SiPMs. This calorimeter, together with a silicon tungsten electromagnetic calorimeter (ECAL) and a scintillator strip Tail Catcher and Muon Tracker (TCMT) will test the PF detector concept with hadron and electron beam data. It is the first large scale application of the SiPMs. Operational experience will be extremely important for the design of a few hundred times larger ILC calorimeter. New types of Multipixel Geiger Photo-Diodes (MGPD) are being developed now by several firms including Hamamatsu. Their comparison is important for the development of the best photo-detectors for the ILC HCAL.

2. The Hadron Calorimeter

The HCAL is a 38-layer sampling calorimeter made of a plastic-scintillator steel sandwich structure with a lateral dimension of about 1×1m^2. Each layer consists of 1.6 cm thick steel absorber plates and a plane of 0.5 cm thick plastic scintillator tiles housed in a steel cassette with two 2 mm thick walls. The tile sizes vary from 3×3 cm^2 for 10×10 tiles in the center of the module, to 6×6 cm^2 in the intermediate region (4×24 tiles), and 12×12 cm^2 (4×5 tiles) in the outer region. In the last eight layers, the granularity is decreased to 6×6 cm^2 in the central region to save the number of channels. Each tile has a 1 mm diameter wavelength-shifting (WLS) fiber inserted into a 2 mm deep groove. The fiber is coupled to a SiPM via an air gap. To increase the light yield, the other fiber end is covered with a mirror. The grooves have a quarter-circle shape in the smallest tiles and a full-circle shape in the other tiles. The sides of each tile are matted to provide a diffuse reflection. The tile faces are covered with a 3M Superradiant foil.

The readout electronics was developed by the Orsay and DESY groups [2]. A VME-based data acquisition system was produced by the UK Calice group [3]. The HCAL is equipped with a LED based calibration system produced

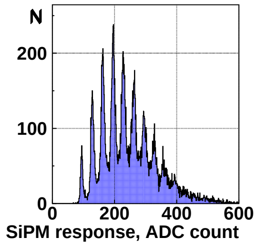

Fig. 1. A typical SiPM spectrum for low-intensity light, showing up to nine individual peaks corresponding to different number of fired pixels.

in Prague [4]. It provides light signals up to 200 Minimum Ionizing Particle (MIP) equivalent individually to each tile.

3. Silicon Photomultipliers

A SiPM is a multipixel silicon photodiode operated in the Geiger mode [1]. These detectors were developed and manufactured by MEPhI/PULSAR in Russia. The SiPM photosensitive area is 1.1×1.1 mm^2. It holds 1156 pixels, with the size of 32×32 μm^2. SiPMs are reversely biased with a voltage of $\sim$ 50 V and have the gain $\sim 10^6$. Once a pixel is fired it produces the Geiger discharge. The analog information is obtained by summing up the number of fired pixels. So the dynamic range is limited by the total number of pixels. Each pixel has a quenching resistor of the order of a few MΩ built in, which is necessary to break off the Geiger discharge. Photons from a Geiger discharge in one pixel can fire neighboring pixels. This leads to a cross talk between pixels. The pixel recovery time is of the order of 100 ns. With smaller resistor values the recovery time reaches about 20 ns and a pixel can fire twice during the pulse from the tile. This leads to a dependence of the SiPM saturation curve on the signal shape which is not convenient. The SiPMs are insensitive to magnetic fields which was tested up to 4 Tesla [1].

More than 10000 SiPMs have been produced by the MEPhI/PULSAR group and have been tested at ITEP. The tests are performed in an automatic setup, where 15 SiPMs are simultaneously illuminated with calibrated light from a bundle of Kuraray Y11 WLS fibers excited by a UV LED . During the first 48 hours, the SiPMs are operated at an increased bias voltage, that is about 2 V above the normal operation voltage. Next, the gain, noise and relative efficiency with respect to a reference photomultiplier are measured as a function of the bias voltage. The bias voltage working point is chosen as the one that yields 15 pixels for a MIP-like signal provided by the calibrated LED.

At the working point, we measure several SiPM characteristics. With low-light intensities of the LED, we record pulse height spectra that are used for the gain calibration. A typical pulse height spectrum is shown in figure 1, in which up to 9 individual peaks corresponding to different number of fired pixels are clearly visible. This excellent resolution is extremely important for calorimetric application

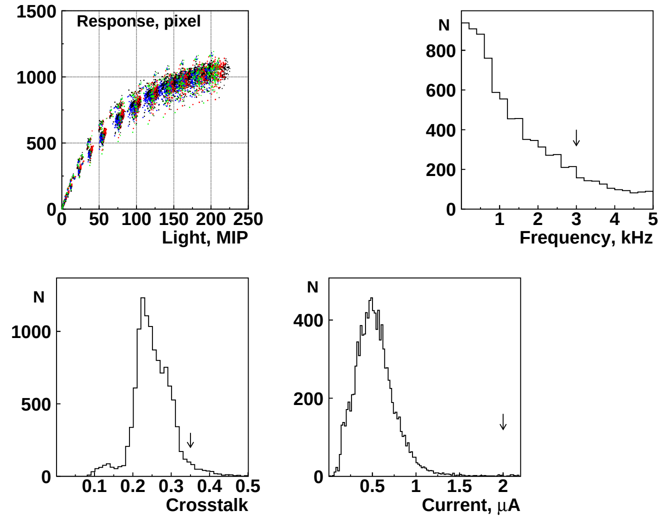

Fig. 2. The response function for SiPMs (upper left); the distribution of SiPM noise at half a MIP threshold (upper right), cross talk (lower left) and current (lower right).

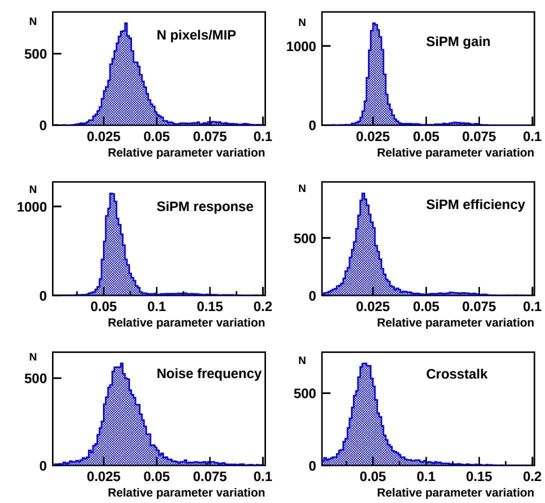

Fig. 3. The relative variation of SiPM parameters for 0.1 V change in bias voltage.

since it allows a self calibration and monitoring of every channel. We record the response function of each SiPM over the entire dynamic range (zero pixel to saturation). Figure 2 shows the number of fired pixels versus the light intensity in units of MIPs for different SiPMs. The shape of the response function of all SiPMs is similar and individual curves are all within 15%. In addition, we measure the noise rate at half a MIP threshold, the cross talk, and the SiPM current. The corresponding distributions are also shown in figure 2. Arrows in figures show the selection cutoff. Figure 3 shows the SiPM parameter relative variation for 0.1 V variation of the bias voltage. The decrease of temperature by 2 °C leads to the decrease of the breakdown voltage by 0.1 V, which is equivalent to the increase of the bias voltage by the same amount. In addition, the decrease

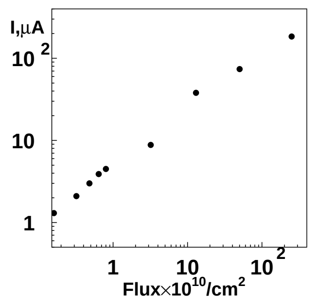

Fig. 4. The SiPM current as a function of flux of 200 MeV protons.

of the temperature leads to the decrease of the SiPM noise.

The first radiation hardness tests of SiPMs have been performed using a proton beam of the ITEP synchrotron. Figure 4 shows the increase in SiPM current with the accumulated flux of 200 MeV protons. The current increase is compatible with that observed in other Si detectors [5]:

$$I = \alpha \cdot F \cdot S \cdot L \cdot G \cdot \epsilon \cdot (1 + X)\,,$$

where F is the proton flux, S is the SiPM area, L is the effective length in which noise charge carriers are produced, ϵ is the probability for a noise carrier to produce the Geiger discharge with the amplification factor G and cross talk X. Using $\alpha = 6 \cdot 10^{-17}$ A/cm [5] we get $L \sim 25\mu$m. SiPMs, however, are more sensitive to radiation damage than other Si detectors because of the high amplification ($\sim 10^6$) and a very low initial noise of about 0.1 photo-electrons. These two properties are important for a clear separation of signals with different number of detected photons as seen in figure 1. This advantage which is important for calibration is lost after an irradiation with about 10^{10} protons/cm^2, because individual pixel peaks cannot be resolved any longer due to noise pile-up. Nonetheless, SiPMs can be still operated even after much larger radiation doses, but they have an increased noise. The radiation hardness of SiPMs is sufficient for operation in a hadron calorimeter at the ILC. Only in the endcaps close to the beam pipe, one can expect a neutron flux above 10^{10}/cm^2/500 fb^{-1}, which would lead to excess currents above 5μA and thus cause a smearing of individual pixel peaks. We have assumed here a standard energy-dependent relative radiation damage efficiency of neutrons and protons [5]. Future tests will study the effect of long-term low-dose irradiation on the aging.

During the production of the first two calorimeter planes we encountered a problem of long not quenched discharges in many SiPMs which appeared after some time. Problematic SiPMs have been studied under a high gain microscope and the reason for the long discharges was found. It was a short circuit between the polysilicon resistor and the Al bus. The distance between them is only 3 μm. This distance will be increased in the next versions of SiPMs. For the existing SiPMs we introduced the 48 hours test at elevated voltage which removes the majority of problematic SiPMs.

4. Test Beam Experience and Future Perspectives

The calorimeter was assembled and commissioned at DESY. The DESY electron test beam was used to obtain an initial MIP calibration of the calorimeter cells [6]. The calorimeter was operated practically without problems at the CERN test beam during 15 weeks initially with 15 and then with 23 planes ($\sim$ 5000 channels). In the planes 3-23 (which were produced after the observation of the long discharge problem) 98% of channels are good, 1% are dead because of the problems in SiPM-signal cable soldering, and 1% are dead because of the long discharges. We have not noticed any deterioration of the calorimeter performance during the 15 weeks of operation.

The TCMT [7] is made of $100 \times 5 \times 0.5$ cm^3 strips with WLS fiber and SiPM readout. All its 16 layers have been installed and demonstrated a stable operation. This technique is a good candidate for the ILC detector muon system [8]. Recent measurements of a $100 \times 2.5 \times 0.5$ cm^3 strip with WLS fiber and SiPM readout at the ITEP synchrotron demonstrated a possibility to reach the time resolution of better than 1 ns. This corresponds to the coordinate resolution of about 15 cm along the strip. In the summer 2007 the complete HCAL and TCMT will be tested at CERN.

The ILC detector cost increases very fast with the increase of the calorimeter thickness. Therefore it is desirable to have as thin detector layers as possible. We have studied at the proton beam of the ITEP synchrotron 3 mm thick 30×30mm^2 tiles with both WLS fiber, and direct coupling of MGPDs. The direct coupling of MGPDs to a tile simplifies considerably the production. Figure 5 shows the tile response uniformity for WLS fiber readout with SiPM and the direct readout with the 2.1×2.1 mm^2 blue-sensitive MRS APD (CPTA-149) from CPTA(Moscow) [9]. The Kuraray 1 mm diameter Y11 fiber was glued inside 2 mm deep grove with an optical glue. The SiPM was also glued to the fiber. The MRS APD was attached with the optical glue at the center of the tile or at the corner. The uniformity and the photo-electron yield are sufficient for the tile with WLS fiber and SiPM readout. There is a large response non-uniformity in case of the direct MGPD couplings. Probably it is possible to improve the uniformity by reducing the reflectivity of the tile. The uniformity requirements for the hadron calorimeter are not high. The photo-electron yield in the plateau region is sufficient. However the noise of the used MRS APDs is too high to resolve individual photo-electron peaks. This makes impossible the auto-calibration of the calorimeter. We consider the auto-calibration to be extremely important for stability monitoring and non-linearity correction.

Recently Hamamatsu has developed a MGPD called MPPC. The MPPC with 1600 channels has a very low noise and good efficiency in the blue region. Figure 6 shows our measurements of the efficiency for green and blue light, gain, and cross-talk for different MGPDs. The MPPC efficiency is measured with about 10% accuracy. The SiPM

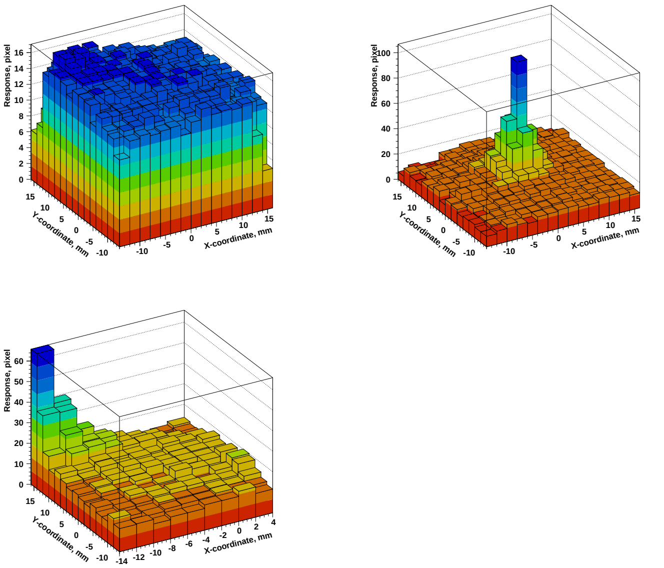

Fig. 5. $3 \times 30 \times 30\,\mathrm{mm}^3$ tile response to MIP; tile with a diagonal fiber and SiPM readout (left), tiles with direct MRS APD readout (middle and right).

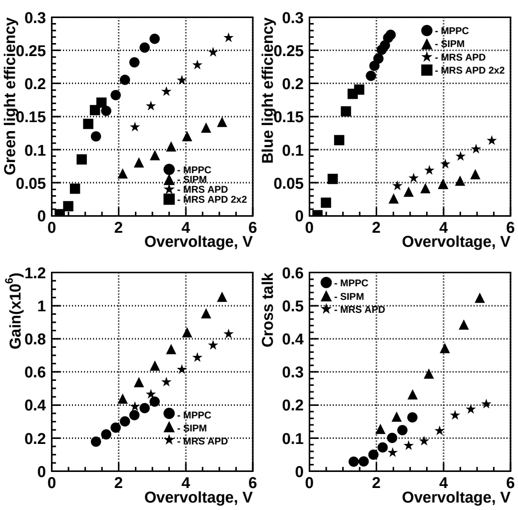

Fig. 6. Parameters of SiPM (triangles), MRS APD CPTA-143 (stars), MRS APD CPTA-149 (squares), and MPPC (dots) as a function of overvoltage.

and MRS APD efficiencies are measured relative to the MPPC efficiency. The green light is the light of a Y11 WLS fiber illuminated with a UV LED. The blue light is the light of the scintillator illuminated with the UV LED. The green-sensitive 1 mm^2 MRS APD (CPTA-143) and MPPC have a smaller cross talk and larger efficiency for the green light than SiPMs. The blue-sensitive 4.4 mm^2 MRS APD (CPTA-149) has efficiency comparable to MPPC both for the green and blue light. We could not measure the efficiency for CPTA-149 at large overvoltages. Individual pixels are not resolved in this photo-detector. Therefore the number of photo-electrons from the LED is determined from the width of the pulse height distribution assuming that it is determined by the Poison fluctuations in the number of photo-electrons. This method stops to work at large overvoltages because the noise becomes too large. The MPPC has a quite high efficiency for the blue light. Unfortunately it is still slightly insufficient for the direct readout of 3 mm thick tiles. The light yield measured at DESY and ITEP is about 7 pixels/MIP for 5 mm thick tiles and 5 pixels/MIP for 3 mm thick tiles. Since the MPPC noise is small the increase of the MPPC area by a factor of two would be adequate for the direct readout of 3 mm thick tiles. The MPPC has two small drawbacks. It has a relatively small gain and a response curve which depends on the duration of the signal.

5. Conclusions

The CALICE HCAL is the first large scale (8 thousand channels) application of the novel photo-detectors - SiPMs. The unique SiPM properties and the elaborated test and selection procedure allowed to construct a reliable and simple in operation calorimeter. The beam tests of HCAL will be very important for the demonstration of the feasibility of the PF method. The developed technique looks adequate for a several hundred times larger ILC hadron calorimeter but a lot of industrialization of this young technology is still required. It is possible (and natural) to use the same technique for the ILC muon system and may be even for the electromagnetic calorimeter. The tile thickness can be reduced to 3 mm. The feasibility of direct coupling of MGPD to a tile without WLS fiber is still under investigation. New MGPDs are being developed by several firms. The final choice of the photo-detector depends on the progress in the MGPD properties and on the overall optimization. The CALICE collaboration designs now a new realistic and scalable HCAL prototype.

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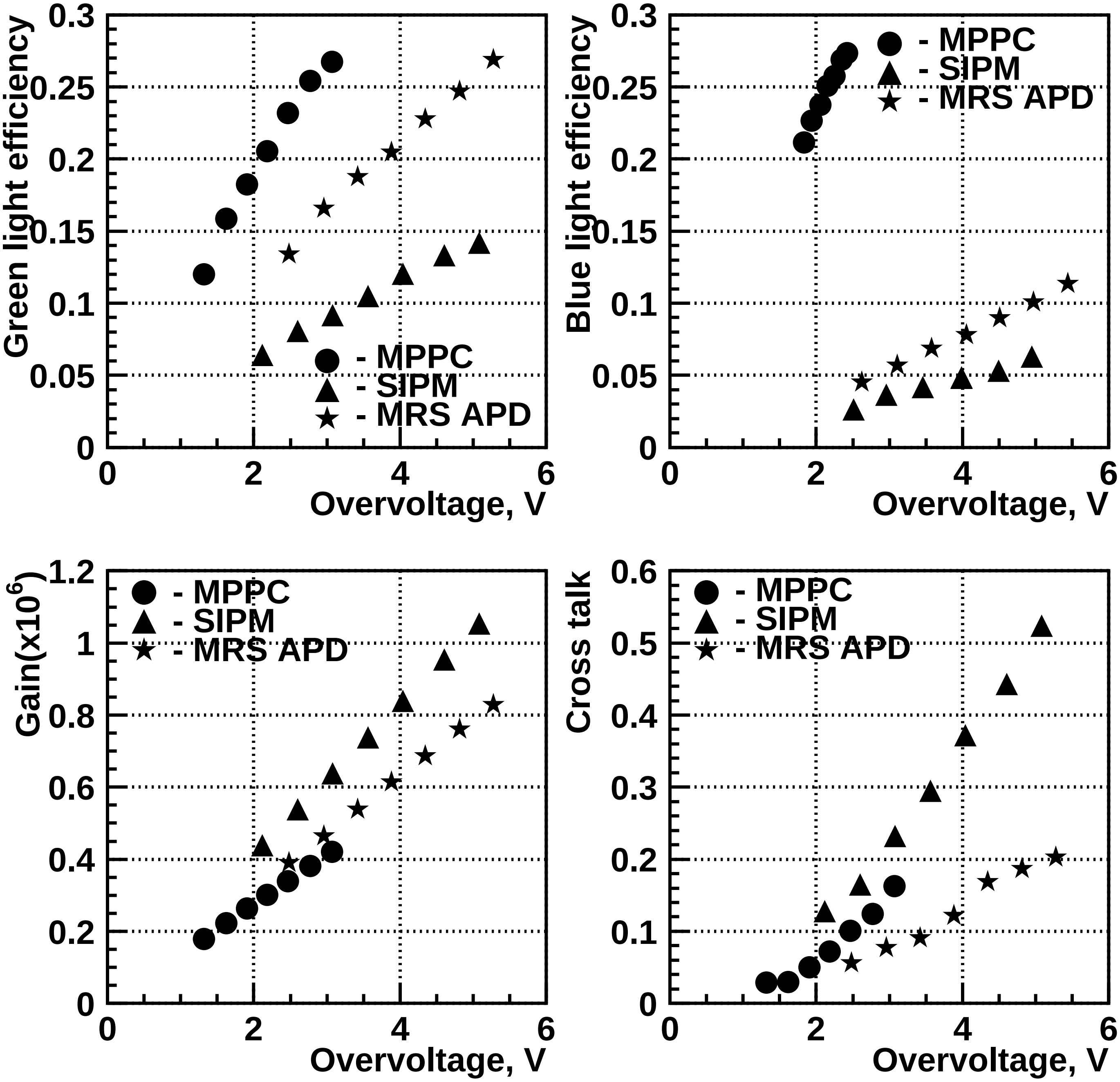
Green light efficiency
Blue light efficiency
Gain(x10^6)
Cross talk
Overvoltage, V
- MPPC
- SIPM
- MRS APD